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(71) Applicants (*for all designated States except US*): NORANDA INC. [CA/CA]; BCE Place, Suite 4100, 181 Bay Street, Toronto, Ontario M5J 2T3 (CA). CANAGRAV RESEARCH LTD. [CA/CA]; 2-1715 27 Avenue N.E., Calgary, Alberta T2E 7E1 (CA).

(72) Inventor; and
(75) Inventor/Applicant (*for US only*): PANENKA, Jerry, R. [CA/CA]; 3428 - 7th Street S.W., Calgary, Alberta T2T 2X9 (CA).

(74) Agent: NADEAU, Francois; Noranda Technology Centre, 240 Boulevard Hymus, Pointe-Claire, Quebec H9R 1G5 (CA).

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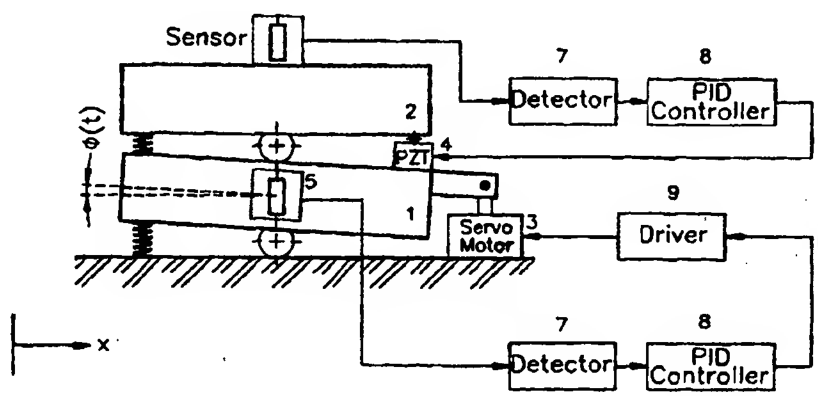

(57) Abstract

A system for compensating for horizontal common-mode acceleration and tilt on a moving platform including a laboratory motion isolation table or borehole logging probe, by transforming horizontal accelerations of the platform into vertical accelerations, comprises a tilt table (1, 2) mounted on the platform, a sensor (5, 6) mounted on the tilt table or on the platform for sensing linear accelerations and tilts to which the platform is subjected, and a tilting device (3, 4) mounted on the platform and responsive to the sensor for tilting the table to compensate for horizontal accelerations and tilts to which the platform is subjected.

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ISOLATION OF ENVIRONMENTAL ACCELERATIONS AND TILTS ON MOVING PLATFORM

This invention relates to a system for compensating for the effects of horizontal accelerations and tilts, on a moving platform, such as an air-, land-, water-, or space-borne vehicle or in a borehole-logging probe, or on a laboratory motion isolation (seismic) table.

Background of the Invention

When carrying out high resolution measurements involving free or partially free masses on a moving platform, it is often desirable to compensate for the effect of horizontal accelerations as well as tilts. For example, let us consider an air-borne gravity gradiometer based either on pendulous or other accelerometer pairs. One way to reduce the effect of horizontal common-mode acceleration on the above sensors is to match the accelerometers over a very broad dynamic range and to closely maintain their alignment. Neither may be attainable to a sufficient degree with present technology.

Tilts can, with expensive gimballed platforms, be maintained to within a few micro-radians. Compensation for horizontal accelerations (which are typically .01 - .02 G during survey regime) has not been accomplished to date.

Statement of Invention

The present invention is based on the principle of equivalence between tilt $\phi(x,)$ and $\phi(y)$ and horizontal accelerations ($\ddot{x}$) or ($\ddot{y}$), which states that an accelerometer cannot distinguish between horizontal acceleration and tilt. Consequently, the effect of x and y on a moving platform can be compensated for by tilting the platform by an angle $\phi(x,y)$,

where $\tan \phi \; (x) = x$

$\tan \phi \; (y) = y$ with $\ddot{x}$ and $\ddot{y}$ expressed in G's

This operation transforms (in platform body co-ordinates), horizontal accelerations $\ddot{x}$, $\ddot{y}$ into a vertical acceleration $\ddot{z}$, to which a pendulous horizontal accelerometer is relatively insensitive. Tilting is the most effective way to compensate for large-amplitude, low-frequency (below 1 Hz) horizontal accelerations. High-frequency, low amplitude motions (vibrations) can be attenuated, for example with a piezo-electric (PZT) driven translational x, y, z stage.

The system in accordance with the present invention comprises a tilt table mounted on a moving platform including a laboratory motion isolation table or a borehole logging probe, a sensor mounted on the tilt table or on the platform for sensing linear accelerations and tilts to which the platform is subjected, and a tilting device mounted on the platform and responsive to the sensor for tilting the tilt table to compensate for horizontal accelerations and tilts to which the platform is subjected.

The sensor may be, for example, a horizontal accelerometer such as the QA 3000 manufactured by Sundstrand Data Control Inc., Redmond, Wash., or an electronic bubble level in closed feedback loop with the tilting device.

The sensor may also be an Inertial Measurement Unit (IMU) like H423 manufactured by Honeywell Inc. of Clearwater, Florida. If an IMU is used as a gravity sensor, it can be, for lower noise, installed on a tilt table in a Shuler-tuned closed loop configuration with the tilting device. Alternatively, the IMU may be a part of an autopilot, motion compensation or other device, working in open-loop configuration with the tilting device.

In the case of accelerometer-based gravity gradiometry, the sensor output may be provided by

accelerometers of the gradiometer pairs. In this application, the sensor may be a part of the feedback loop with the tilting device thus substantially eliminating the horizontal common-mode component of the gravity gradient signal.

The sensor output signal is preferably processed through a feedback controller for applying a regulated feedback control to the tilting device to cause the sensor base to tilt by an angle that will compensate for horizontal accelerations and tilts. The feedback controller is preferably a proportional-integral-derivative feedback controller.

The tilt table may be a two-stage table comprising a first coarsely controlled stage using a servo-motor as a tilting device, and a second finely controlled stage using a transducer as a tilting device.

The sensor and tilting device may be combined in a single sensor/tilting unit. The sensor/tilting unit may be a critically-damped pendulum or a "dish" filled with liquid, on which the tilt table floats. In either cases a feedback controller will not be required for the first coarse stage.

Short Description of the Drawing

The invention will now be disclosed, by way of example, with reference to preferred embodiments illustrated in the accompanying drawings in which:

Figure 1 shows a two-stage, two degrees of freedom (DOF), pitch and roll, active motion isolation table configuration which will attenuate residual horizontal accelerations and tilts;

Figure 2 shows a single-stage, DOF (pitch and roll), active motion isolation table configuration; and

Figure 3 shows a two-stage, active motion isolation table configuration similar to Figure 1 which will additionally attenuate vibrations along x, y and z axes (five or six DOF).

Detailed Description of a Preferred Embodiment

Referring to Figure 1, there is shown a two-stage tilt table in the form of a coarsely-controlled table 1 and a finely-controlled table 2, which are affected by linear acceleration disturbance (t) and angular tilt disturbance (t). In accordance with the present invention, both of these disturbances are compensated for by tilting the sensor base by angle O (table 2), using a servo-motor 3 operating a precision lead screw (not shown) to provide a linear displacement to a resolution of about 5 - 10 micro-radians. For greater resolution than can be achieved with a mechanical device, a piezoelectric device (PZT) device, or electro - strictive or magneto-strictive (EST or MST respectively), or any other suitable transducer 4 is mounted on table 1 to provide a resolution of the order

of 10 nano-radians or better.

For the purpose of the description, it is assumed that the disturbances to be compensated for are in the (x, z) vertical plane of motion. The tilt tables may however be modified to accommodate motions in all six degrees of freedom.

In the present embodiment, the sensors are pendulous acceleration sensors 5 and 6, which are mounted on tables 1 and 2 respectively to sense horizontal accelerations (and tilts). The output voltage V(t) of each accelerometer is sensed by a detector 7 and fed to a feedback controller 8 which applies a feedback voltage to the servo-motor or the PZT through a suitable driver 9 if required to thereby null the output voltages V(t) of the pendulous accelerometers.

For less demanding applications, a single-stage, two-DOF tilt table, as illustrated in Figure 2, may provide a simpler, less expensive alternative. The disturbances sensed by sensor 10 mounted on table 11 are applied to a feedback controller 12 or 13 or both. Coarse deviations may be compensated by a servo-motor 14 through a suitable driver 15 while fine deviations of the order of 10 nano-radians may be compensated by a PZT 16.

On a seismic isolation table, where compensating tilts may be limited to several micro-radians, a PZT (or EST or MST) stage only can be used.

Figure 3 is a two-stage stabilized platform configuration such as shown in Figure 1 wherein stage 2 additionally includes a x,y,z vibration isolation stage which is part of the tilt table. In this embodiment high frequency low-amplitude vibrations can be attenuated with x,y,z translation devices such as piezo-electric (PZT) devices 4, 16, 17 working in closed loop with a suitable triaxial vibration sensor 18.

The configuration shown in Figure 3 can accommodate five degrees of freedom. The sixth degree (yaw compensation) is not shown but can be added using the same technique.

A Proportional-Integral-Derivative (PID) feedback control is preferably used to stabilize the table as a function of the pendulum output where:

$$e = KpV + Kd\,V + Ki \int Vdt + Vn$$

where e = voltage applied to the PZT

Kp	=	proportional control gain
Ki	=	integral control gain
Kd	=	derivative control gain
Vn	=	electronic noise

If the tilt assembly is critically damped (i.e. no control induced oscillations) then the gains of each

control component are related such that:

$$K^2p - 4\ KdKi > 0$$

$$\text{and}\quad \omega c = Ki/Kp < 0.1\ \text{Hz}$$

such that integral control is used effectively where it is needed most (in this case for frequencies ωc less than 0.1 Hz).

All modes of PID control are needed because:

1) Proportional: is usually needed with integral and derivative control.

2) Integral: is required for reducing the steady state tilt angle in the feedback loop because tilt frequencies close to DC require a high gain.

3) Derivative: for decreasing the feedback response time at high frequencies as well as applying a phase-lead control.

Although the invention has been disclosed, by way of example, with reference to preferred embodiments, it is to be understood that it is not limited to such embodiments and that other alternatives are also envisaged within the scope of the following claims:

CLAIMS

1. A system for compensating for horizontal common-mode acceleration and tilt on a moving platform including a laboratory motion isolation table or borehole logging probe, by transforming horizontal accelerations of the platform into vertical accelerations, comprising:

   a) a tilt table mounted on the platform;

   b) a sensor mounted on the tilt table or on the platform for sensing linear accelerations and tilts to which the platform is subjected; and

   c) a tilting device mounted on the platform and responsive to the said sensor for tilting the tilt table to compensate for horizontal accelerations and tilts to which the platform is subjected.

2. A system as defined in claim 1, wherein the sensor is a horizontal accelerometer or an electronic bubble level, in closed feedback loop with the said tilting device.

3. A system as defined in claim 1, wherein in case of accelerometer-based gravity gradiometry using accelerometer pairs, the sensor output is provided by at least one accelerometer of the gradiometer pairs, in closed feedback loop with the said tilting device.

4. A system as defined in claim 1, wherein the sensor

is an Inertial Measurement Unit (IMU), which may be installed either on a tilt table capable of working in a Shuler-tuned closed loop configuration with the tilting device, or separately in open loop configuration with the tilting device, as a part of an autopilot, motion compensation or other device.

5. A system as defined in claim 1, further comprising a feedback controller responsive to the output of the sensor for applying a regulated feedback control to the tilting device to cause the table to tilt by an angle that will compensate for horizontal accelerations and tilts.

6. A system as defined in claim 5, wherein the feedback controller is a proportional-integral-derivative feedback controller.

7. A system as defined in claim 1 wherein said tilt table is a two-stage table comprising a first coarsely controlled stage using a servo-motor as a tilting device, and a second finely-controlled stage using a transducer as a tilting device.

8. A system as defined in claim 7, wherein the second stage includes a high frequency vibration insolation stage comprising x, y,z translation devices responsive to vibration sensors.

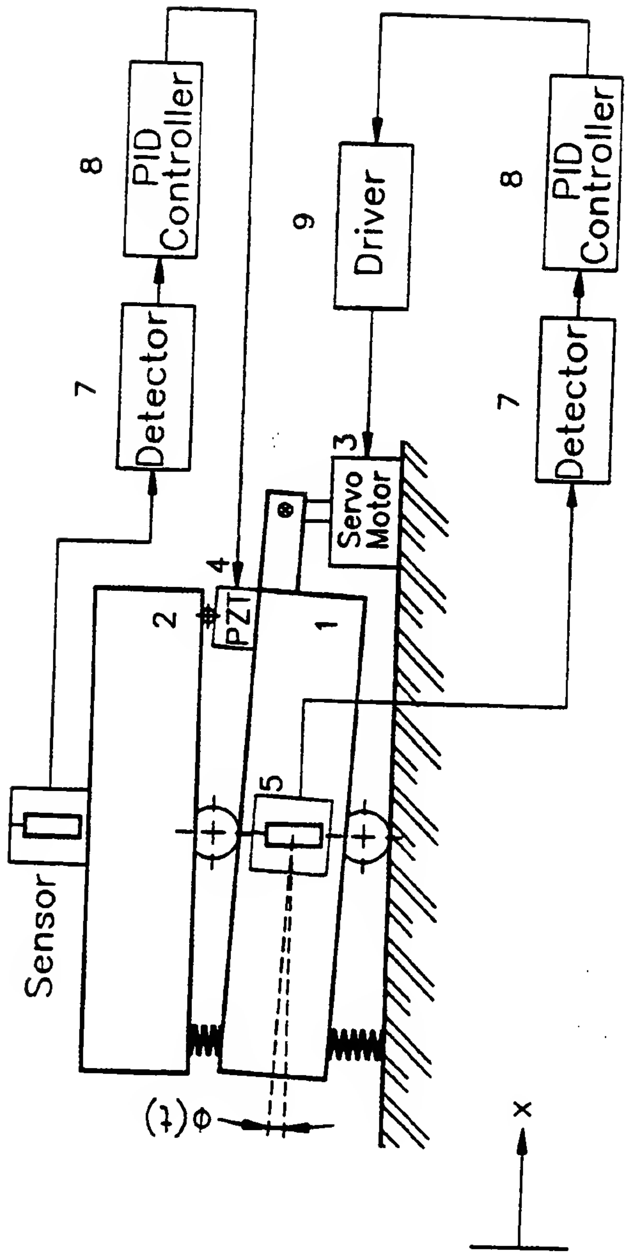
9. A system as defined in claim 7, wherein the sensor

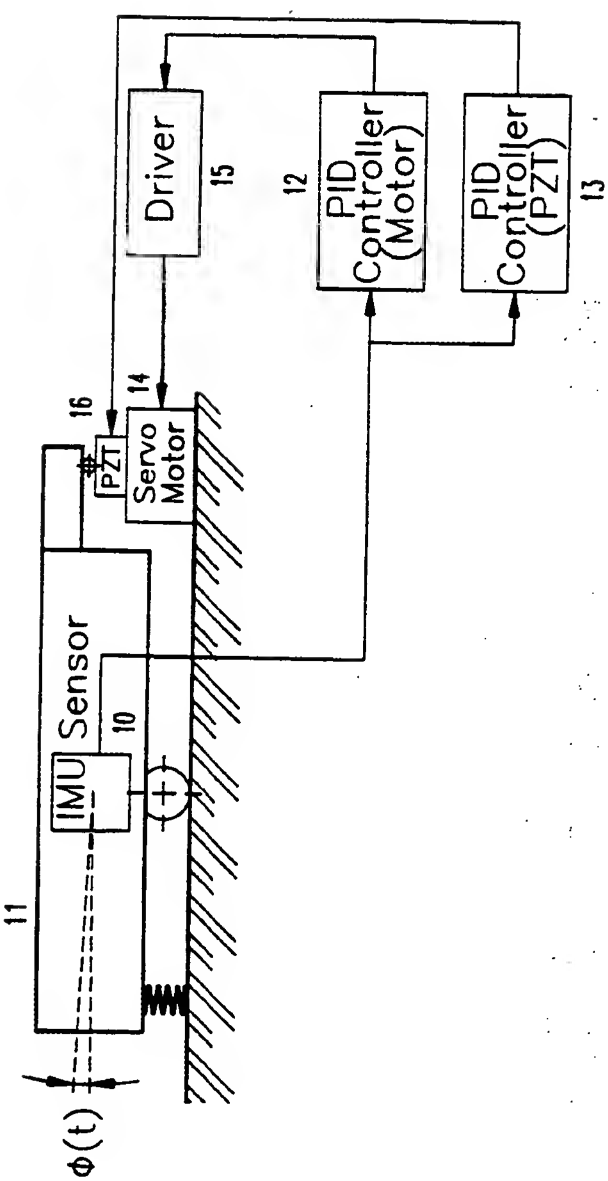
and tilting device are combined in a single sensor/tilting unit.

10. A system as defined in claim 9, wherein the sensor/tilting unit is a critically-damped pendulum.

11. A system as defined in claim 9, wherein the sensor/tilting unit is a dish filled with liquid, on which the tilt table floats.

Fig. 1


8
PID Controller
7
Detector
9
Driver
8
PID Controller
7
Detector
3
Servo Motor
4
PZT
2
1
5
Sensor
φ(t)
x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12
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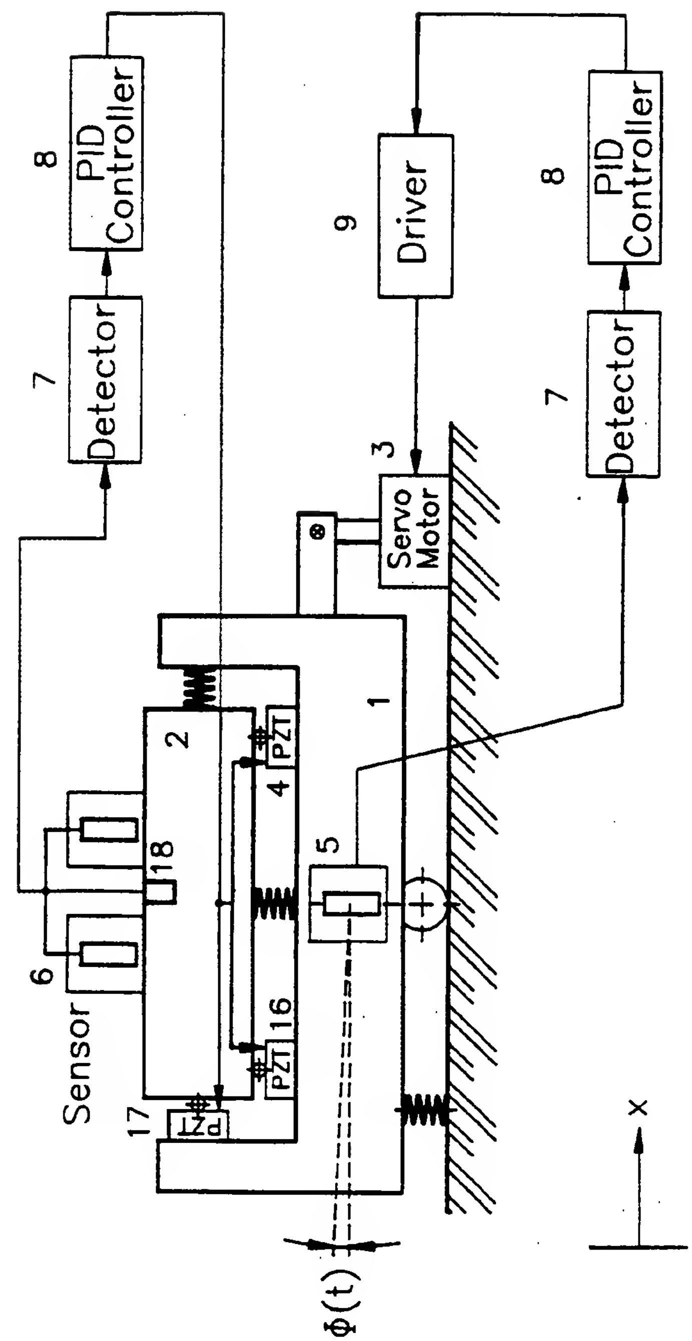
PID Controller (PZT)
13
16
14
PZT
Servo Motor
Sensor
10
IMU
11
φ(t)

Fig. 2.

Fig. 3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7
Detector
9
Driver
8
PID Controller
7
Detector
3
Servo Motor
1
2
PZT
4
5
18
6
Sensor
16
PZT
17
PZT
Φ(t)
x

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 94/00441

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01C9/08 G01V7/16 G01C21/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01C G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	FR,A,1 525 230 (SAGEM) 17 May 1968 see the whole document ---	1,2,5 3
Y	US,A,3 668 932 (HANSEN) 13 June 1972 see abstract ---	3
A	US,A,3 015 962 (WRIGLEY ET AL.) 9 January 1962 see the whole document -----	1

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☒ Patent family members are listed in annex.

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17 November 1994	13. 12. 94

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INTERNATIONAL SEARCH REPORT

Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
FR-A-1525230		NONE	
US-A-3668932	13-06-72	NONE	
US-A-3015962		NONE	